US009348235B2

(12) **United States Patent**
Hoshino

(10) **Patent No.: US 9,348,235 B2**
(45) **Date of Patent: May 24, 2016**

(54) **EXPOSURE APPARATUS AND METHOD OF MANUFACTURING DEVICE**

(71) Applicant: **CANON KABUSHIKI KAISHA**, Tokyo (JP)

(72) Inventor: **Tomohiro Hoshino**, Utsunomiya (JP)

(73) Assignee: **CANON KABUSHIKI KAISHA**, Tokyo (JP)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **14/453,944**

(22) Filed: **Aug. 7, 2014**

(65) **Prior Publication Data**

US 2015/0049315 A1 Feb. 19, 2015

(30) **Foreign Application Priority Data**

Aug. 13, 2013 (JP) 2013-168336

(51) **Int. Cl.**

G03B 27/68	(2006.01)
G03B 27/42	(2006.01)
G03F 7/20	(2006.01)

(52) **U.S. Cl.**

CPC ***G03F 7/70483*** (2013.01); ***G03F 7/70308*** (2013.01)

(58) **Field of Classification Search**

CPC G03F 7/70308; G03F 7/20
USPC 355/52, 53, 55, 67
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

6,563,564	B2 *	5/2003	de Mol et al.	355/52
2002/0036758	A1	3/2002	De Mol et al.	
2002/0039845	A1 *	4/2002	Yoshimura	438/784
2009/0028421	A1 *	1/2009	Sukegawa	382/144
2013/0137050	A1 *	5/2013	Takahashi et al.	430/325

FOREIGN PATENT DOCUMENTS

JP	63-016725	B2	4/1988
JP	2002-015997	A	1/2002

* cited by examiner

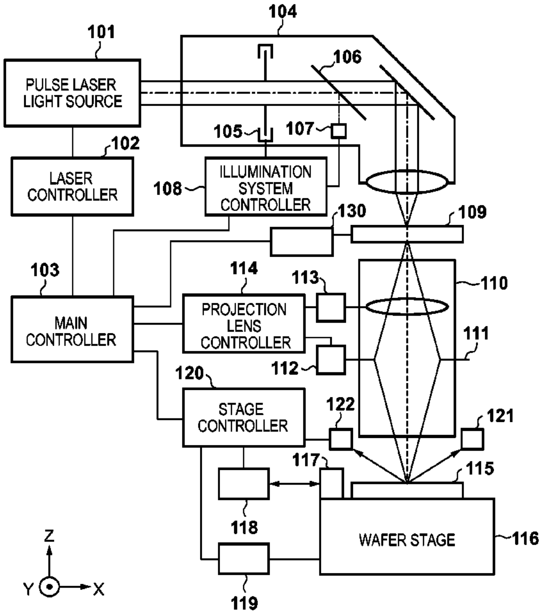
Primary Examiner — Hung Henry Nguyen

(74) *Attorney, Agent, or Firm* — Rossi, Kimms & McDowell LLP

(57) **ABSTRACT**

An exposure apparatus projects an image of a pattern formed on a mask onto a substrate through a projection optical system. The exposure apparatus includes: a prediction unit configured to predict an imaging characteristic fluctuation of the projection optical system which is caused by thermal action due to exposure, by using a model formula modeling the imaging characteristic fluctuation; and a correction unit configured to correct the imaging characteristic based on a prediction result obtained by the prediction unit. The model formula includes a composition of a plurality of functions modeling the imaging characteristic fluctuation and indicating a time dependency, each of the plurality of functions having an exposure-angle-of-view dependency and the exposure-angle-of-view dependencies of the plurality of functions being different from each other.

6 Claims, 4 Drawing Sheets


101
PULSE LASER LIGHT SOURCE
102
LASER CONTROLLER
103
MAIN CONTROLLER
104
106
105
107
108
ILLUMINATION SYSTEM CONTROLLER
130
109
110
111
113
114
PROJECTION LENS CONTROLLER
112
120
STAGE CONTROLLER
122
121
117
115
118
WAFER STAGE
116
119
Z
Y
X

F I G. 1

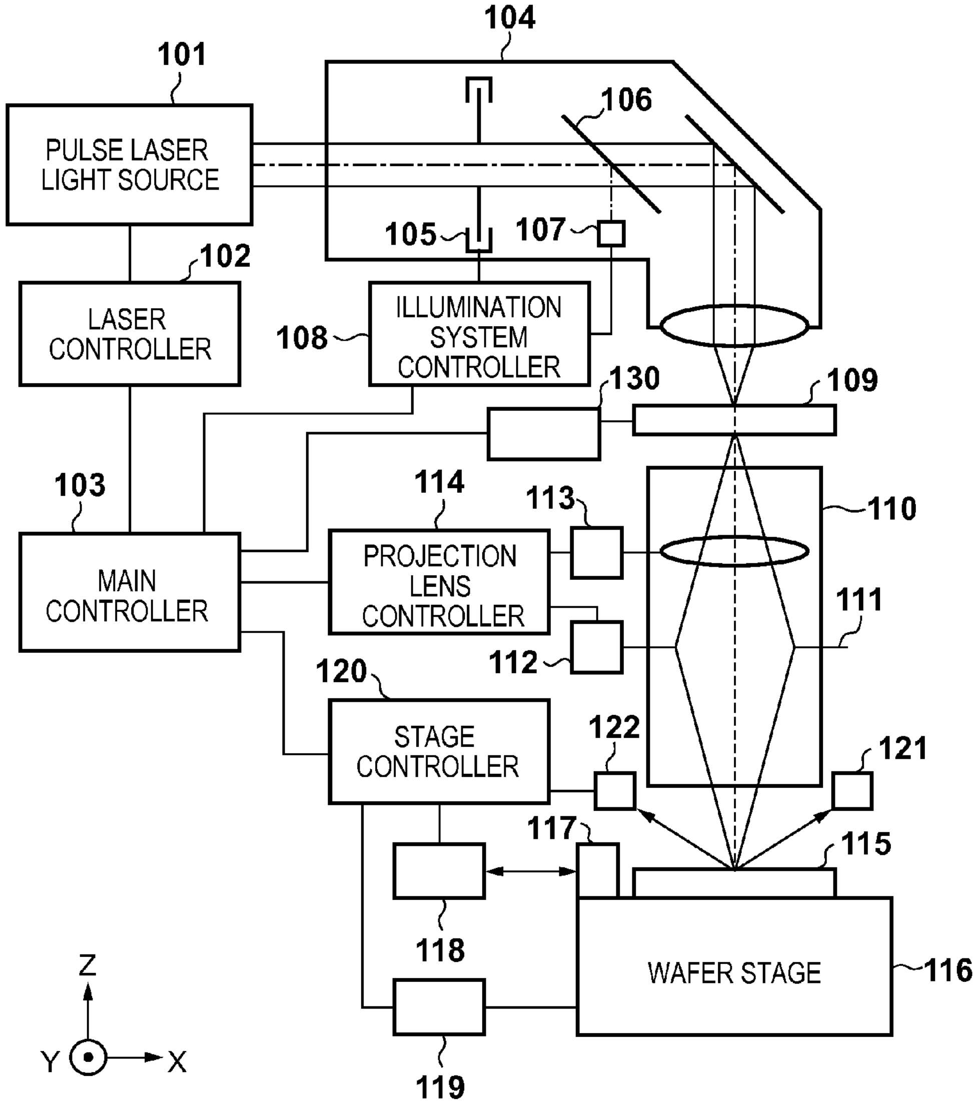

104
101
106
PULSE LASER
LIGHT SOURCE
105
107
102
LASER
CONTROLLER
108
ILLUMINATION
SYSTEM
CONTROLLER
130
109
103
114
113
110
MAIN
CONTROLLER
PROJECTION
LENS
CONTROLLER
111
112
120
STAGE
CONTROLLER
122
121
117
115
118
WAFER STAGE
116
Z
Y
X
119

FIG. 2

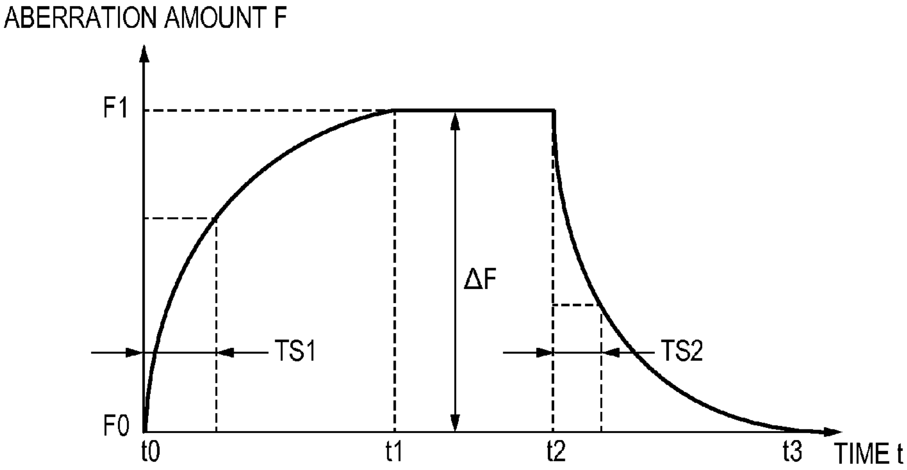


FIG. 3A

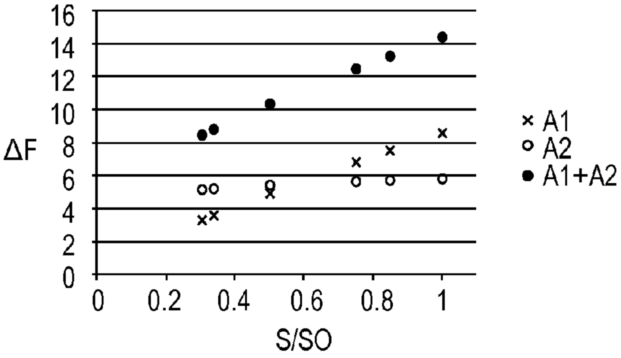


FIG. 3B

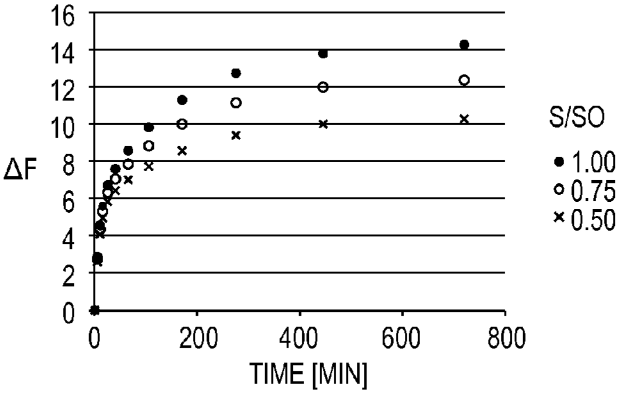


FIG. 4A

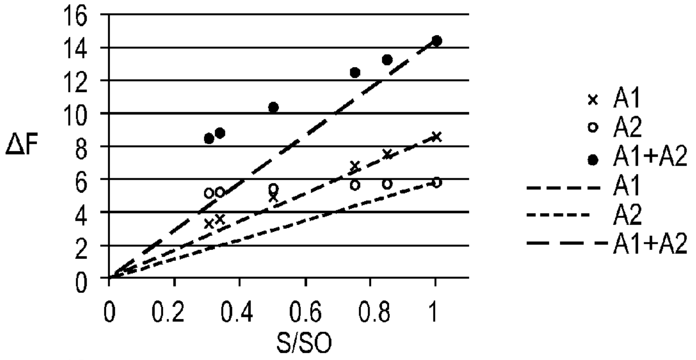


FIG. 4B

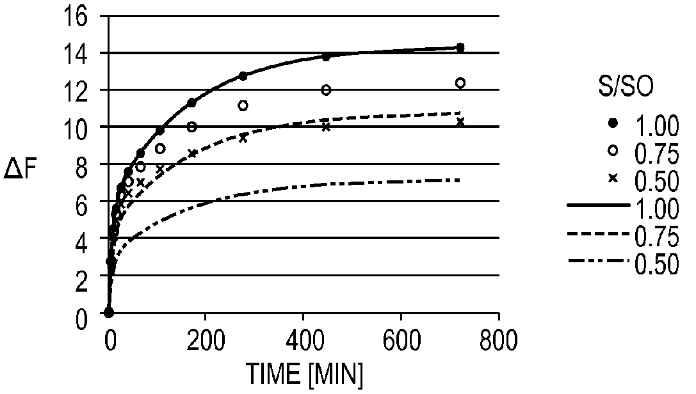


FIG. 5A

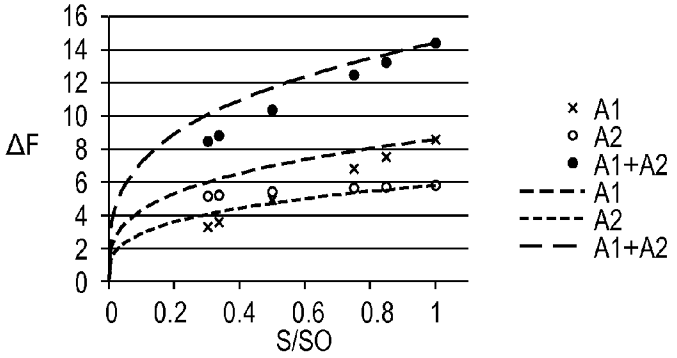


FIG. 5B

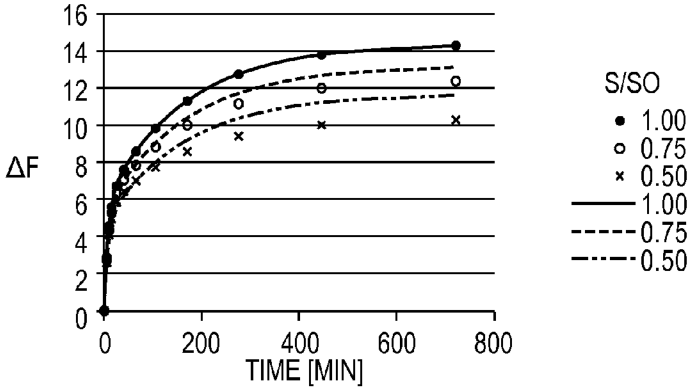


FIG. 6A

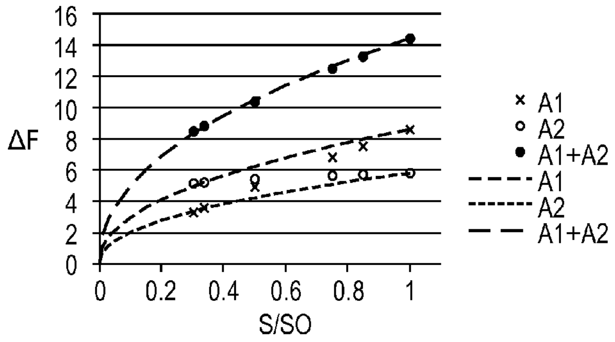


FIG. 6B

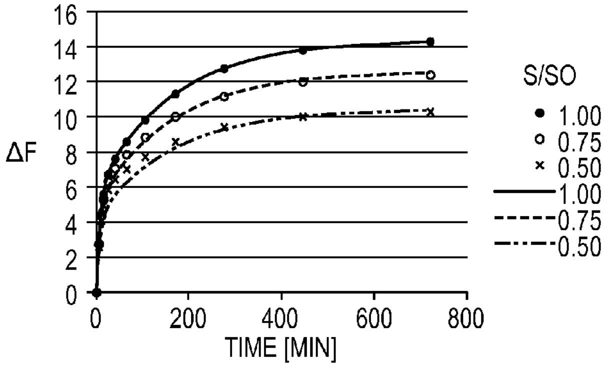


FIG. 7A

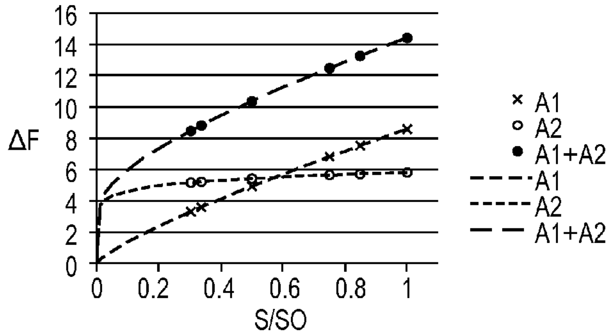
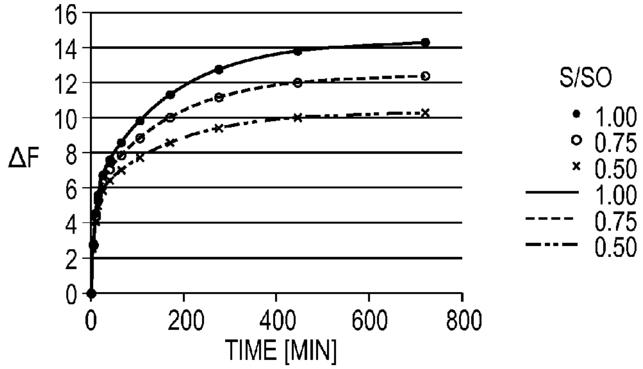


FIG. 7B



EXPOSURE APPARATUS AND METHOD OF MANUFACTURING DEVICE

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to an exposure apparatus and a method of manufacturing a device.

2. Description of the Related Art

In a manufacturing process for a semiconductor device formed from an ultrafine pattern, such as an LSI and a VSLI, a reduction projection exposure apparatus is used, which performs reduction exposure of a circuit pattern drawn on a mask (reticle) onto a substrate (wafer) coated with a photosensitive agent to form a print pattern. With an increase in the packaging density of semiconductor devices, demands have arisen for further micropatterning. Along with the development of a resist process, exposure apparatuses have been increasingly required to cope with micropatterning.

As a means for increasing the resolving power of an exposure apparatus, there are available a method of changing an exposure wavelength to a shorter wavelength and a method of increasing the NA (Numerical Aperture) of a projection optical system. As the resolving power increases, the focal depth of the projection optical system decreases. It is therefore an important theme to improve the focus accuracy of matching the imaging plane (focal plane) of the projection optical system with a wafer surface.

In addition, one of the important optical characteristics of the projection exposure apparatus is the alignment accuracy of accurately superimposing the respective patterns throughout, a plurality of steps. Important factors that influence this alignment accuracy include a magnification error in the projection optical system. As the size of a pattern used for a VLSI has tended to decrease year by year, there have been increasing needs for an improvement in alignment accuracy. It is therefore very important to keep the magnification of the projection optical system at a predetermined value.

The projection optical system absorbs part of exposure energy. It is known that the temperature of the projection optical system changes due to the heat generated by the absorption, and the optical characteristics of the projection optical system, such as the refractive exponent, change. If the projection optical system is kept irradiated with exposure light for a long time, imaging characteristics of the projection optical system (for example, a focus, curvature of field, magnification, distortion, astigmatism aberration, and wavefront aberration) fluctuate. As a result, a line width error, alignment error, and the like may occur by an amount which cannot be neglected in terms of the device manufacture.

For this reason, there has been proposed a method of compensating for imaging characteristic fluctuations depending on the irradiated state of exposure energy onto the projection optical system. For example, according to Japanese Patent Publication No. 63-16725, the amount of fluctuation in imaging characteristic depending on the exposure energy state of a projection optical system is computed by a model formula using an exposure amount, an exposure time, a non-exposure time, and the like as variables, and the imaging characteristic fluctuation of the projection optical system is corrected based on the computation result. The above model formula has a coefficient unique to the projection optical system for each imaging characteristic. Properly setting this coefficient can obtain and correct the imaging characteristic fluctuation of the projection optical system.

In addition, there has been proposed an exposure apparatus which can obtain a higher resolving power with respect to the projection of a specific pattern by changing an illumination shape. In such an apparatus, the light source distribution generated on the pupil plane of a projection optical system changes depending on exposure conditions (for example, a projection system NA, the numerical aperture of an illumination system, an exposure area, an exposure center position, and a mask used for exposure), and hence the amounts of fluctuation in imaging characteristics occurring for the respective exposure conditions differ from each other.

Therefore, in order to accurately correct fluctuations in imaging characteristics depending on the above light source distribution state of illumination light, it is necessary to calculate correction coefficients optimal for exposure conditions from differences in the light source distribution state of illumination light on the pupil plane, reticle transmittance, exposure area, scanning speed, exposure amount, irradiation time, and the like.

However, correction coefficients differ for the respective exposure conditions, and it requires much time to grasp a thermal fluctuation phenomenon accompanying exposure. Japanese Patent Laid-Open No. 2002-15997 discloses a method of predicting the imaging characteristic fluctuation caused by lens heating, by using, for example, the following model formula:

$$F(t)=A_1(1-e^{-t/\tau 1})+A_2((1-e^{-t/\tau 2} \tag{1}$$

where τ_1 and τ_2 are time constants, and A_1 and A_2 are amplitudes.

In addition, the amplitudes A_1 and A_2 are expressed as follows, assuming linear dependencies on some of the parameters indicating the amplitudes, especially parameters proportional to power entering a lens, such as a light intensity, the size of an imaging plane, a reticle transmittance, and a wafer reflectance.

$$A_1=\mu_1 \cdot Tr \cdot S \cdot I \cdot W_{refl} \tag{2}$$

$$A_2=\mu_2 \cdot Tr \cdot S \cdot I \cdot W_{refl} \tag{3}$$

where I is an exposure intensity (W/m^2), S is the size of an imaging plane at the wafer level or a mask area (m^2), Tr is a reticle transmittance (a pure fraction or percentage), W_{refl} is a wafer reflectance (a pure fraction or percentage), and μ_1 and μ_2 are correction coefficients. As described above, as a model formula for predicting an imaging characteristic fluctuation, a model formula is known to be obtained by modeling assuming a linear dependency on a parameter proportional to power entering the lens.

However, as in the case of the model formula described above, if the dependencies of the amplitudes A_1 and A_2 on an exposure angle of view are assumed in a linear form in the same manner, it is not possible to properly predict an imaging characteristic in a time zone immediately after the activation of the apparatus or a change in exposure condition, in which a fluctuation is relatively large.

In consideration of the above point, the present invention provides an exposure technique capable of predicting a change in imaging characteristic of the projection optical system upon a change in exposure angle of view and correcting the imaging characteristic.

SUMMARY OF THE INVENTION

According to one aspect of the present invention, there is provided an exposure apparatus which projects an image of a pattern formed on a mask onto a substrate through a projection optical system, the apparatus comprising: a prediction unit configured to predict an imaging characteristic fluctuation of the projection optical system which is caused by thermal action due to exposure, by using a model formula modeling the imaging characteristic fluctuation; and a correction unit configured to correct the imaging characteristic based on a prediction result obtained by the prediction unit, wherein the model formula comprises a composition of a plurality of functions modeling the imaging characteristic fluctuation and indicating a time dependency, each of the plurality of functions having an exposure-angle-of-view dependency and the exposure-angle-of-view dependencies of the plurality of functions being different from each other.

According to the present invention, it is possible to predict an imaging characteristic fluctuation of a projection optical system even upon a change in exposure angle of view and correct the imaging characteristic. It is possible to properly predict an imaging characteristic fluctuation and correct the imaging characteristic even upon a change in energy distribution entering a projection optical system upon a change in exposure angle of view.

Further features of the present invention will become apparent from the following description of exemplary embodiments (with reference to the attached drawings).

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a block diagram showing the arrangement of an exposure apparatus according to an embodiment;

FIG. **2** is a graph showing an example of the aberration fluctuation characteristic of a projection optical system;

FIGS. **3**A and **3**B are graphs each showing an example of the prediction result of the imaging magnification fluctuation characteristic of the projection optical system;

FIGS. **4**A and **4**B are graphs each showing an example of the prediction result of the imaging magnification fluctuation characteristic of the projection optical system;

FIGS. **5**A and **5**B are graphs each showing an example of the prediction result of the imaging magnification fluctuation characteristic of the projection optical system;

FIGS. **6**A and **6**B are graphs each showing an example of the prediction result of the imaging magnification fluctuation characteristic of the projection optical system; and

FIGS. **7**A and **7**B are graphs each showing an example of the prediction result, of the imaging magnification fluctuation characteristic of the projection optical system.

DESCRIPTION OF THE EMBODIMENTS

Embodiments of the present invention will be described in detail below with reference to the accompanying drawings. Note that the constituent elements described in the embodiments are merely examples. The technical scope of the present invention is determined by the scope of claims and is not limited by the following individual embodiments.

Assume that in this specification, an imaging characteristic includes at least one of a focus, curvature of field, magnification, distortion, astigmatism aberration, spherical aberration, coma aberration, and wavefront aberration. As is known in this technical field, a wavefront aberration is expressed as each term obtained when a wavefront shape is expanded using Zernike polynomials. In addition, they are sometimes collectively referred to as "aberrations".

First Embodiment

FIG. **1** is a block diagram showing the schematic arrangement of a scanning exposure apparatus (to be also simply referred to as an exposure apparatus hereinafter) according to this embodiment. The exposure apparatus projects a pattern formed on a mask onto a substrate via a projection optical system. Referring to FIG. **1**, a pulse laser light source **101** is sealed with a gas such as KrF or ArF and emits laser light. The pulse laser light source **101** emits, for example, 193-nm light in the far-ultraviolet region. The pulse laser light source **101** includes a front mirror forming a resonator, a diffraction grating for narrowbanding an exposure wavelength, and a narrowbanding module formed from a prism and the like. In addition, the pulse laser light source **101** includes a monitor module which is formed from a spectroscope, a detector, and the like and monitors wavelength stability and a spectral width. Furthermore, the pulse laser light source **101** is provided with a shutter and the like.

A laser controller **102** and a main controller **103** of the overall exposure apparatus perform gas exchange control of the pulse laser light source **101**, control for wavelength stability, control of an applied discharge voltage, and the like. In this embodiment, the laser controller **102** controls the pulse laser light source **101** in accordance with an instruction from the main controller **103** of the overall exposure apparatus instead of performing independent control alone.

The beam emitted from the pulse laser light source **101** is shaped into a predetermined beam shape via the beam shaping optical system (not shown) of an illumination optical system **104**. The shaped beam further enters an optical integrator (not shown) to form many secondary light sources for illuminating a reticle **109** (to be described later) with a uniform illuminance distribution.

The aperture portion of an aperture stop **105** of the illumination optical system **104** has an almost circular shape. An illumination system controller **108** can set the diameter of the aperture portion, and then the NA (Numerical Aperture) of the illumination optical system **104** to desired values. In this case, since the value of the ratio between the numerical aperture of the recording medium **110** (to be described later) and the numerical aperture of the illumination optical system **104** is a coherence factor (σ value), the illumination system controller **108** can set a σ value by controlling the aperture stop **105** of the illumination system.

A half mirror **106** is arranged on the optical path of the illumination optical system **104**. Part of exposure light illuminating the reticle **109** is reflected by the half mirror **106** to be extracted. A photosensor **107** for ultraviolet light is arranged on the optical path of reflected light from the half mirror **106** to generate an output corresponding to the intensity of exposure light (exposure energy). An integration circuit (not shown) which performs integration for each pulse emission by the pulse laser light source **101** converts an output from the photosensor **107** into exposure energy per pulse, and inputs it to the main controller **103** which controls the exposure apparatus main body via the illumination system controller **108**.

The reticle (or mask) **109** is used as an original. A circuit pattern of a semiconductor device which is to be printed is formed on the reticle **109**, and is irradiated with light by the illumination optical system **104**. A projection optical system **110** is arranged to reduce a circuit pattern image on the reticle **109** at a reduction magnification β (for example, $\beta=\frac{1}{4}$) and focus/project the image on one shot area on a wafer **115** as a photosensitive substrate coated with a photoresist. The reticle **109** is held on a reticle stage (mask stage) (not shown) which holds a reticle (mask). A reticle stage controller **130** (mask stage control unit) can control the position and posture (angle) of the reticle **109** by driving the reticle stage.

An aperture stop **111** of the projection optical system **110** which has an almost circular aperture portion is arranged on the pupil plane (the Fourier transform plane for a reticle) of the projection optical system **110**. A driving unit **112** such as a motor can set the aperture diameter to a desired value by controlling the diameter of the aperture portion.

A field lens driving device **113** (driving unit) moves a field forming part of a lens system (optical element) in the projection optical system **110** on the optical axis of the projection optical system **110** by using an air pressure, piezoelectric element, or the like. This reduces a distortion error by optimizing the projection magnification while preventing the influences of various aberrations of the projection optical system **110**.

A projection lens controller **114** controls the driving unit **112** and the field lens driving device **113** (driving unit) under the control of the main controller **103**.

A wafer stage **116** (substrate stage) which holds a wafer can move in the three-dimensional directions, and can move in the optical axis direction (Z direction) of the projection optical system **110** and within a plane (X-Y plane) perpendicular to the optical axis direction. A laser interferometer **118** measures the distance from a moving mirror **117** fixed on the wafer stage **116** to detect the X-Y plane position of the wafer stage **116**. A stage controller **120** (substrate stage control unit) can control the position or posture (angle) of the wafer **115** by driving the wafer stage **116**.

The stage controller **120** under the control of the main controller **103** of the exposure apparatus detects the position of the wafer stage **116** by using the laser interferometer **118**, and controls a driving unit **119** such as a motor to move the wafer stage **116** to a position within a predetermined X-Y plane.

In addition, a projection optical system **121** and a detection optical system **122** constitute a focus plane detection unit. The projection optical system **121** projects a plurality of light beams formed from non-exposure light which does not expose the photoresist on the wafer **115**. Each light beam is focused on the wafer **115** and reflected. Each light beam reflected by the wafer **115** enters the detection optical system **122**.

In the detection optical system **122**, a plurality of position detection light-receiving elements (not shown) are arranged in correspondence with the respective reflected light beams, and the light-receiving surface of each position detection light-receiving element, is almost conjugated to the reflection point of each light beam on the wafer **115** by an imaging optical system. The positional shift of the wafer **115** surface in the optical axis direction of the projection optical system **110** is measured as the positional shift of an incident light beam on the corresponding position detection light-receiving element in the detection optical system **122**.

The following will describe a model formula for the aberration fluctuation (imaging characteristic fluctuation) of the projection optical system **110** due to the irradiation of exposure energy and correction coefficients for compensating for an imaging characteristic fluctuation for each exposure condition, which are used to quantify the model formula according to this embodiment.

FIG. **2** shows an example of a secular change in aberration of the projection optical system **110** which is caused by exposure. The abscissa represents time t, and the ordinate, an aberration amount F of the projection optical system **110** at a given image height. Aberrations in this case include, for example, a focus, curvature of field, magnification, distortion aberration, astigmatism aberration, spherical aberration, and coma aberration. In addition, an aberration fluctuation amount ΔF generally takes different values at the respective image heights. Letting F0 be the initial value of an aberration amount as an imaging characteristic value of the projection optical system **110**, when the projection optical system **110** starts exposure by using the pulse laser light source **101** at time t**0**, the aberration fluctuates with time and stabilizes to a predetermined aberration amount F1 at time t**1**. Subsequently, even if exposure light is kept applied to the projection optical system **110**, the energy absorbed by the projection optical system **110** to generate heat and the heat energy emitted by the projection optical system **110** reach an equilibrium state, and the aberration amount does not change from F1. When the exposure stops at time t**2**, the aberration amount returns to the initial value with time. At time t**3**, the aberration amount becomes the initial aberration amount F0.

Time constant TS1 and TS2 in FIG. **2** are equivalent to time constants in the heat transfer characteristic of the projection optical system **110**. These time constants and the maximum fluctuation amount F1 are values unique to the projection optical system **110**, and differ for each aberration. Therefore, such values need to be determined for each apparatus and each aberration.

However, it requires a predetermined time or more to grasp a thermal fluctuation phenomenon, and it requires much time to obtain the maximum fluctuation amount F1 under many exposure conditions. The maximum fluctuation amount F1 differs for each exposure condition. In addition, it is difficult to completely grasp a thermal fluctuation phenomenon accompanying exposure.

Under the circumstances, an imaging characteristic fluctuation caused by lens heating is expressed by using a model formula, and the maximum fluctuation amounts F1 under a minimum number of exposure conditions are obtained at the time of examination to efficiently predict an imaging characteristic fluctuation for each exposure condition. In this case, the main controller **103** executes the prediction of an imaging characteristic fluctuation. The main controller **103** controls the illumination system controller **108**, the reticle stage controller **130**, the projection lens controller **114** (control unit), and the stage controller **120** based on the prediction result of an imaging characteristic fluctuation. At least, one of the illumination system controller **108**, the reticle stage controller **130**, the projection lens controller **114**, and the stage controller **120** performs control using the prediction result obtained by the prediction unit to correct the imaging characteristic.

An imaging characteristic fluctuation is expressed by, for example, the following exponential model formula. The model formula is the composition of a plurality of functions representing time dependencies modeling imaging characteristic fluctuations. Each function $A_i(1-e^{-t/\tau i})$ has a dependency on an exposure angle of view. An exposure-angle-of-view dependency will foe described later with reference to equations (7) to (10).

$$F(t)=A_1(1-e^{-t/\tau 1})+A_2(1-e^{-t/\tau 2})+\ldots+A_i(1-e^{-t/\tau i}) \tag{4}$$

where i is a natural number, τ_i is a time constant, and A_i is the amplitude of each exponential function. Each function is defined for each coefficient, (parameter) τ_i and each A_i, and equation (4) represents a common function. Since the right-hand side of equation (4) converges to $e^{-t/\tau i}=0$ with respect to $t\rightarrow\infty$, the maximum fluctuation amount F1 is given by $F1=A_1+A_2+\ldots+A_i$.

In order to cope with various exposure conditions, the model formula generally uses the time constant τ_i and the amplitude A_i as functions of several exposure parameters, for example, a projection system numerical aperture NA, illumination system σ value, light intensity, exposure angle of view, reticle transmittance, and wafer reflectance.

If, however, for example, the time constant τ_i is used as a continuous variable with respect to the projection system numeral aperture NA, illumination system σ value, and exposure angle of view, it is necessary to countlessly add imaging characteristic predictions using different time constants every time these exposure conditions are changed. This is not preferable for the system.

For this reason, in general, the amplitude A_i is expressed as a function of several exposure parameters, for example, the projection system numeral aperture NA, illumination system σ value, light intensity, exposure angle of view, reticle transmittance, and wafer reflectance by using a finite number of time constants τ_i for each projection system.

In addition, the number of exponential functions to be combined can be set to about 2 or 3 as an optimal number sufficient to achieve the required accuracy for the projection system. However, the spirit of the present invention is not limited to this example.

An imaging magnification will be exemplified as an imaging characteristic. FIGS. **3**A and **3**B show the relationship between imaging magnification fluctuation and exposure angle of view when, for example, an imaging magnification fluctuation is expressed by an exponential function model formula by using two time constants. The ordinate in each of FIGS. **3**A and **3**B represents deviations (imaging magnification fluctuations: ΔF) from an ideal imaging magnification, and time constants τ_1 and τ_2 are, for example, τ_1=10000 sec and τ_2=500 sec.

FIG. **3**A shows an imaging magnification fluctuation (ΔF) with respect to an exposure-angle-of-view ratio (S/S0) for the coefficients (A_1 and A_2 in equation (4)) obtained by fitting using two time constants set in advance. Referring to FIG. **3**A, "x", "○", and "•" respectively represent A_1, A_2, and A_1+A_2. The abscissa of FIG. **3**A represents the ratio (exposure-angle-of-view ratio: S/S0) obtained by normalizing an exposure angle S of view with a maximum exposure angle S0 of view of the apparatus.

FIG. **3**B is a graph plotting imaging magnification fluctuations (ΔF) at the respective exposure angles of view as a function of time. Note that this graph represents imaging magnification fluctuations at S/S0=1.0, 0.75, and 0.5 as typical exposure-angle-of-view ratios, but omits imaging magnification fluctuations at other exposure angles of view.

Referring to FIGS. **3**A and **3**B, assume that exposure conditions except for an exposure angle of view are constant conditions, including, for example, the projection optical system numeral aperture NA, illumination system σ value, light intensity (indicating, to be precise, a reticle irradiation energy per unit exposure area), reticle transmittance, and wafer reflectance.

At the time of examination of the projection optical system, A_1 and A_2 at the maximum exposure angle of view of the apparatus are obtained as $A0_1$ and $A0_2$, respectively. A_1 and A_2 at the time of a change in exposure angle of view are predicted by a model formula using parameters that change power entering the lens, such as an exposure angle of view, reticle transmittance, and wafer reflectance.

Assuming a proportional relationship with each parameter, A_1 and A_2 are represented by

$$A_1=A0_1\cdot Tr\cdot(S/S0)\cdot I\cdot W_{ref1} \tag{5}$$

$$A_2=A0_2\cdot Tr\cdot(S/S0)\cdot \mathrm{I}\cdot \mathrm{W}_{ref1} \tag{6}$$

where I is an exposure intensity (W/m^2), S is a set exposure angle of view (m^2), S0 is a maximum exposure angle of view (m^2), Tr is a reticle transmittance, W_{ref1} is a wafer reflectance, and $A0_1$ and $A0_2$ are coefficients calculated from the amount of imaging magnification fluctuation at the maximum exposure angle S0 of view.

A_1 and A_2 at the time of a change in exposure angle of view are predicted in the manner shown in FIGS. **4**A and **4**B. The relationships between the ordinates and the abscissas in FIGS. **4**A and **4**B are the same as those in FIGS. **3**A and **3**B. FIG. **4**B is a graph plotting imaging magnification fluctuations (ΔF) as a function of time by using the coefficients A_1 and A_2 in FIG. **4**A. A fluctuation characteristic predicted value F(t) of an imaging magnification at the time of a change in exposure angle of view exhibits a predetermined difference from an actual imaging magnification fluctuation. If this difference does not satisfy the required accuracy of the projection system, A_1 and A_2 are respectively expressed as follows, assuming that the maximum exposure angle of view of the projection exposure system is S0 and proportional to the power of a ratio S/S0 of S0 to the set exposure angle S of view. In equations (7) and (8), the symbol "^" represents power computation.

$$A_1=\mu_1\cdot Tr\cdot(S/S0)\hat{}C\cdot I\cdot W_{ref1} \tag{7}$$

$$A_2=\mu_2\cdot Tr\cdot(S/S0)\hat{}C\cdot I\cdot W_{ref1} \tag{8}$$

In this case, a power exponent C is a constant, defining an exposure-angle-of-view ratio dependency, and is determined in advance for each system by simulations or from experimental results.

A_1 and A_2 at the time of a change in exposure angle of view are predicted in the manner shown in FIG. **5**A. FIG. **5**B is a graph plotting imaging magnification fluctuations as a function of time by using the coefficients A_1 and A_2. The relationships between the ordinates and the abscissas in FIGS. **5**A and **5**B are the same as those in FIGS. **3**A and **3**B. An imaging magnification predicted value at the time of a change in exposure angle of view can foe approximated to an actual imaging magnification fluctuation by modeling the imaging magnification predicted value at the time of a change in exposure angle of view with respect to an exposure angle of view by using a specific function.

Assume that the fluctuation predicted value F(t) of an imaging magnification at the time of a change in exposure angle of view exhibits a predetermined difference from an actual imaging magnification fluctuation and does not satisfy the required accuracy of the projection system in spite of the use of such a model formula. In this case, modeling is further performed upon adjustment of a constant C. For example, there is conceivable a method of approximating the fluctuation predicted value F(t) to the actual imaging magnification fluctuation by adjusting the constant C based on actual apparatus data.

For example, as shown in FIG. **3**B, an imaging magnification fluctuation is obtained as a function of time by changing the exposure-angle-of-view ratio of the exposure angle S of view to the maximum exposure angle S0 of view of the projection exposure system from 1.0 to ¾ or ½. The coefficients A_1 and A_2 are then calculated from the obtained imaging magnification fluctuation and each exposure-angle-of-view ratio.

The constant C is determined from the obtained set of A_1 and A_2 so as to minimize the difference between the fluctuation predicted value F(t) of an imaging magnification and the actual imaging magnification fluctuation.

Optimizing the constant C in this manner can further improve the prediction accuracy. A_1 and A_2 at the time of a change in exposure angle of view become the values shown in FIG. **6**A.

As shown in FIG. **6**B, however, according to this model formula, the energy absorbed by the projection optical system to generate heat and the heat energy emitted by the projection optical system reach an equilibrium state. Even if a state in which an imaging magnification is stable can be accurately predicted, it is sometime impossible to accurately predict a state in which an imaging magnification greatly changes on the way from the start of exposure to an equilibrium state or on the way to an equilibrium state after the stop of exposure or a change in exposure condition.

In the embodiment of the present invention, therefore, a model formula for predicting an imaging magnification fluctuation is defined as follows. In equations (9) and (10), C_1 and C_2 are constants that define an exposure-angle-of-view ratio dependency and determined in advance for each system by simulations or from experimental results.

$$A_1=\mu_1\cdot Tr\cdot(S/S0)\hat{}C_1\cdot I\cdot W_{ref1} \tag{9}$$

$$A_2=\mu_2\cdot Tr\cdot(S/S0)\hat{}C_2\cdot I\cdot W_{ref1} \tag{10}$$

In this case, the power indices C_1 and C_2 are different constants defining an exposure-angle-of-view ratio dependency. C_1 and C_2 are determined in advance from experimental results. A_1 and A_2 at the time of a change in exposure angle of view are predicted in the manner shown in FIG. **7**A. FIG. **7**B is a graph plotting imaging magnification fluctuations as a function of time by using the coefficients A_1 and A_2. A model using the constants C_1 and C_2 defining an exposure-angle-of-view ratio dependency can accurately predict a state in which an imaging magnification is stable after the energy absorbed by the projection optical system to generate heat and the heat energy emitted by the projection optical system reach an equilibrium state. In addition, this model can accurately predict a state in which an imaging magnification greatly changes on the way from the start of exposure to an equilibrium state or on the way to an equilibrium state after the stop of exposure or a change in exposure condition.

According to the model formula represented by equations (9) and (10), it is possible to accurately predict an imaging magnification fluctuation and minimize errors.

The main controller **103** (prediction unit) predicts an imaging magnification fluctuation by using the above model formula. The main controller **103** controls the illumination system controller **108**, the reticle stage controller **130**, the projection lens controller **114**, and the stage controller **120** based on the prediction result.

The illumination system controller **108**, the reticle stage controller **130**, the projection lens controller **114**, and the stage controller **120** function as a correction unit which corrects an imaging magnification fluctuation based on the prediction result obtained by the prediction unit. The illumination system controller **108**, the reticle stage controller **130**, the projection lens controller **114**, and the stage controller **120** can correct the imaging characteristic by performing control using the prediction result.

This embodiment has exemplified an imaging magnification fluctuation. Obviously, however, the projection optical system can exhibit an exposure-angle-of-view dependency different from that described above depending on the arrangement. In such a case, a model formula may be set, which has a set of optimal time constants and an angle-of-view dependency for each time constant.

In addition, this embodiment has exemplified an imaging magnification fluctuation. However, the embodiment can be applied to any imaging characteristic fluctuation caused by thermal action (ex. the absorption of heat and heat release) by a lens or a mirror upon exposure by a projection optical system, and can be applied to, for example, a focus, curvature of field, distortion, astigmatism aberration, and wavefront aberration.

In addition, this embodiment has exemplified the scanning exposure apparatus. However, the embodiment can be applied to a stepper exposure apparatus of the step & repeat scheme. The scanning exposure apparatus is generally configured to change an exposure angle of view based on the illumination size in the X direction and the scanning distance in the Y direction. If the illumination size in the Y direction does not fluctuate, there is no problem in reading a parameter which determines the incident area of exposure light on the projection optical system as the illumination size in the X direction.

Unlike in the scanning exposure apparatus, in the stepper type exposure apparatus, an imaging characteristic fluctuation does not simply depend on an exposure angle of view, and the imaging characteristic sometimes fluctuates depending on the sizes of a shot in the X and Y directions. In this case, for example, it is effective to set a model formula for a set of optimal time constants and an angle-of-view dependency corresponding to each time constant by using the sizes of a shot in the X and Y directions as parameters.

Second Embodiment

A method of manufacturing a device according to an embodiment of the present invention is suitable for manufacturing an element having a microstructure, such as a semiconductor device or liquid crystal display device. For example, a semiconductor device is manufactured through a pre-process of forming an integrated circuit on a wafer (substrate) and a post-process of completing, as a product, the integrated circuit chip on the wafer formed in the pre-process. The pre-process includes a step of exposing an image of a pattern on a mask onto a wafer coated with a photosensitive agent by illuminating the mask using the exposure apparatus, and a step of developing the wafer. The post-process includes an assembly step (dicing and bonding) and a packaging step (encapsulation).

For example, a liquid crystal display device is manufactured through a process of forming a transparent electrode. The process of forming a transparent electrode includes a step of applying a photosensitive agent to a glass substrate on which a transparent conductive film is deposited, a step of exposing the glass substrate coated with the photosensitive agent using the exposure apparatus described above, and a step of developing the glass substrate. The device manufacturing method in this embodiment is more advantageous than a conventional method in terms of at least one of the device performance, quality, productivity, and production cost.

Although the embodiments of the present invention have been described above, the present invention is not limited to these embodiments and can be variously modified and changed within the spirit and scope of the invention.

While the present invention has been described with reference to exemplary embodiments, it is to be understood that the invention is not limited to the disclosed exemplary embodiments. The scope of the following claims is to be accorded the broadest interpretation so as to encompass all such modifications and equivalent structures and functions.

This application claims the benefit of Japanese Patent Application No. 2013-168336, filed Aug. 13, 2013, which is hereby incorporated by reference herein in its entirety.

What is claimed is:

1. An exposure apparatus which projects an image of a pattern formed on a mask onto a substrate through a projection optical system, the apparatus comprising:

a prediction unit configured to predict an imaging characteristic fluctuation of the projection optical system which is caused by thermal action due to exposure, by using a model formula modeling the imaging characteristic fluctuation; and

a correction unit configured to correct the imaging characteristic based on a prediction result obtained by the prediction unit,

wherein the model formula comprises a composition of a plurality of functions modeling the imaging characteristic fluctuation and indicating a time dependency, each of the plurality of functions having an exposure-angle-of-view dependency which represents a dependency of an illumination size, a size of an imaging plane at the wafer level or a mask area, and the exposure-angle-of-view dependencies of the plurality of functions being different from each other.

2. The apparatus according to claim **1**, wherein each of the plurality of functions has a coefficient defined by a power of a ratio obtained by normalizing a set exposure angle of view with a maximum exposure angle of view of the projection optical system and the plurality of functions differ in a value of an exponent of the power from each other.

3. The apparatus according to claim **1**, wherein the prediction unit predicts, as the imaging characteristic, at least one fluctuation of a focus, curvature of field, magnification, distortion, astigmatism aberration, and wavefront aberration of the projection optical system by using the model formula.

4. The apparatus according to claim **1**, wherein the correction unit comprises a control unit configured to control a driving unit configured to control an aperture stop of the projection optical system and a driving unit configured to move an optical element of the projection optical system,

wherein the control unit performs the control so as to correct the imaging characteristic by using a prediction result obtained by the prediction unit.

5. The apparatus according to claim **4**, wherein the correction unit further comprises

a mask stage control unit configured to control a position or angle of the mask by driving a mask stage holding the mask, and

a substrate stage control unit configured to control a position or angle of the substrate by driving a substrate stage holding the substrate,

wherein the mask stage control unit and the substrate stage control unit perform the control so as to correct the imaging characteristic by using a prediction result obtained by the prediction unit.

6. A method of manufacturing a device, the method comprising:

a step of exposing a substrate by using an exposure apparatus; and

a step of developing the exposed substrate,

wherein the exposure apparatus projects an image of a pattern formed on a mask onto the substrate through a projection optical system, and

the exposure apparatus includes:

a prediction unit configured to predict an imaging characteristic fluctuation of the projection optical system which is caused by thermal action due to exposure, by using a model formula modeling the imaging characteristic fluctuation; and

a correction unit configured to correct the imaging characteristic based on a prediction result obtained by the prediction unit,

wherein the model formula comprises a composition of a plurality of functions modeling the imaging characteristic fluctuation and indicating a time dependency, each of the plurality of functions having an exposure-angle-of-view dependency which represents a dependency of an illumination size, a size of an imaging plane at the wafer level or a mask area, and the exposure-angle-of-view dependencies of the plurality of functions being different from each other.

* * * * *